Rainfall Sequence Effects on Phosphorus Loss in Surface Runoff from Pastures that Received Poultry Litter Application

T. Demissie, D. E. Storm, M. S. Friend, N. T. Basta, M. E. Payton, M. D. Smolen, H. Zhang

Abstract. *Land application of poultry litter to pasture elevates the concentration of phosphorus in surface runoff, and it is becoming an increasing problem in sensitive water bodies. The objectives of this study were to assess the effects of soil test phosphorus (STP), surface application of poultry litter, rainfall/runoff sequences, and time after litter application on dissolved reactive phosphorus (DRP) in surface runoff from pasture in a greenhouse experiment using rainfall simulation. Treatment factors were poultry litter at a rate of 0.0 and 6.7 Mg ha^{-1}, low and high STP, and three rainfall/runoff sequences (RRS). The latter refers to runoff-producing rainfall events starting from day 1, day 4, and day 7 after litter application. The study also included a rainfall simulation study of pasture field plots to investigate the effects of poultry litter and time after application on DRP in surface runoff, which was used to corroborate the greenhouse study. In both studies, runoff samples were taken at the end of 30 min of continuous runoff. Treatment effects on DRP concentrations in surface runoff were analyzed using ANOVA procedures using an alpha = 0.05. For the greenhouse study, poultry litter application, RRS, and time after litter application were found to have a highly significant effect on DRP concentration in surface runoff. Poultry litter had a significant effect on DRP concentrations in surface runoff until 18 days after litter application compared to the controls. Between 18 and 32 days after litter application, the effect on DRP became insignificant for any level of STP or rainfall sequence. A rainfall event without runoff reduced DRP concentration in the first surface runoff events by more than 50%. For the field plot study, DRP decreased rapidly with time, thereby corroborating the greenhouse study. The effect of poultry litter on DRP became statistically insignificant sometime between 35 and 161 days after application.*

Keywords. *Greenhouse study, Permanent pasture, Phosphorus loss, Poultry litter, Rainfall simulator, Rainfall/runoff sequence, Time to initiate runoff, Soil test phosphorus, Water quality.*

The rapid expansion and intensification of poultry production in the Ozark highlands of northeast Oklahoma, northwest Arkansas, and southwest Missouri is associated with a large amount of litter phosphorus production (Edwards and Daniel, 1993). Poultry litter is traditionally applied to meet nitrogen demands of pastures with little considerations given to phosphorus levels in the litter. It contains the major nutrients nitrogen, phosphorus, and potassium in unbalanced proportion for pasture requirements. If applied to meet nitrogen requirements, poultry litter supplies too much phosphorus (Griffiths, 2007), and repeated application of poultry litter elevates soil phosphorus content (Sharpley et al., 1993). In addition, higher rates of poultry litter application result in increased phosphorus levels in runoff (Eghball et al., 2002). Hence, there is a need to carefully manage continual surface application of poultry litter to minimize phosphorus impacts on offsite water quality.

Phosphorus is an essential nutrient for maintaining crop and animal production. The beneficial impacts of poultry litter as a fertilizer have been recognized in the production of several forages (Huneycutt et al., 1988). Because the bulky nature of the litter limits transportation, generally much of the litter is applied to fields close to the production facility (Bosch and Napit, 1992). Poultry litter that was once considered a resource is increasingly seen as a waste (Sharpley et al., 2000). In other words, there is not enough agricultural land to use all of the phosphorus in litter (Sims et al., 2000). As a result, there is an increasing challenge to balance phosphorus inputs as litter phosphorus fertilizer with phosphorus uptake on pastures in poultry litter producing areas. Phosphorus transport in surface runoff from pastures in the Ozark highlands is believed to be one of the most important contributing factors to eutrophication of nearby water bodies (Edwards and Daniel, 1993). Phosphorus additions to surface water from pastures are a concern because the offsite transport of excess phosphorus often results in eutrophication of surface waters (Sharpley et al., 2000; Sims et al., 2000; Daniel et al., 1993). The offsite transport of phosphorus depends on soil phosphorus content, soil properties, rainfall intensity

Submitted for review in April 2010 as manuscript number SW 8507; approved for publication by the Soil & Water Division of ASABE in July 2010.

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Vol. 53(4): 1147-1158 ISSN 2151-0032

and amount, poultry litter rate and time of application, and time between litter application and the first runoff event (Sharpley, 1997; Storm et al., 1996a, 1996b; Storm et al., 1995; Edwards et al., 1994; Sharpley et al., 1994).

Edwards and Daniel (1993) documented the importance of poultry litter application rate, rainfall intensity, and the interval between litter application and the first surface runoff event on the amount of nutrients in surface runoff. Of these factors, the least information is available on the combined effects of non-runoff producing rainfall events, timing of rainfall application relative to first runoff events, and time after litter application on DRP concentration in surface runoff from pastures. The study of the effects of different scenarios of surface runoff producing or non-runoff producing rainfall events on phosphorus transport from pastures will be helpful in developing guidelines and recommendations for the timing of land application of poultry litter in order to minimize the offsite water quality impacts (Storm et al., 1996b). This is specifically true of the Ozark highlands of northeast Oklahoma and southwest Missouri, where large amounts of poultry litter are generated and surface applied to nearby pasture fields.

Objectives of the Study

The objectives of this study were: (1) to assess the effects of soil test phosphorus (STP), surface application of poultry litter, rainfall/runoff sequences (RRS), and time (days) after litter application on dissolved reactive phosphorus (DRP) in surface runoff from boxes in a controlled greenhouse experiment using simulated rainfall; (2) to investigate the effect of poultry litter application rate and days after litter application on DRP in surface runoff from field plot pastures using simulated rainfall; and (3) to assess if the field study corroborates the greenhouse study.

Rainfall Sequence vs. Time Interval and Days After Litter Application

DRP in surface runoff is highly sensitive to a non-runoff producing rainfall event combined with the time interval between litter application and the first runoff event, i.e., the rainfall/runoff sequence (Storm et al., 1996b). Because most of the phosphorus from litter applications is lost in the first runoff event (Sharpley, 1995), several researchers investigated the effect of time interval between litter application and a runoff-producing rainfall event on phosphorus loss. These investigations showed that most of the phosphorus in the surface-applied litter is lost in the first runoff events (Edwards et al., 1994; Storm et al., 1995; Storm et al., 1996b; Sharpley, 1997; Sauer et al., 1999). After an initial spike, phosphorus concentration in runoff declines rapidly with time (Heathman et al., 1995; Storm et al., 1996b; Sharpley, 1997; Schroeder et al., 2004). These studies also showed a decrease in phosphorus concentration in runoff with an increase in days after litter application (Westerman and Overcash, 1980; Edwards et al., 1994; Storm et al., 1996b; Pierson et al., 2001) or incorporation of poultry litter into the soil (Sharpley, 1997).

The time interval between litter application and the first runoff event has an influence on DRP, particulate phosphorus (PP), and total phosphorus (TP) concentrations (Eghball et al., 2002). Studies carried out to investigate the factors affecting phosphorus export from pastures suggested that the management of fertilizer application related to timing (time gap) to the first runoff event after litter application appears to be a primary method to minimize the offsite transport of phosphorus (Pote et al., 2003; Pierson et al., 2001; Nash et al., 2000; Storm et al., 1996b; Storm et al., 1995).

Poultry Litter Application

The effect of surface-applied poultry litter manifests itself on the chemical, nutrient, and physical characteristics primarily in the top 5 cm of the soil (Sharpley et al., 1993). A strong relationship exists between the rate of litter application and the concentration of DRP, TP, and PP in runoff (Schroeder et al., 2004; Pote et al., 2001; Kleinman and Sharpley, 2003), where phosphorus concentrations in runoff typically increase with an increase in poultry litter application rate (Storm et al., 1996a).

Soil Test Phosphorus

STP is an index of how much phosphorus is available for plant use. It neither indicates total phosphorus in the soil nor the amount of phosphorus that can be lost in surface runoff. Further, the analyses differ from state to state and even from lab to lab (Sims et al., 2000). Linear relationships between STP and DRP in surface runoff have been obtained by various researchers; however, these relationships are generally specific to soil type (Sharpley, 1995; Pote et al., 1996; Davis, 2002), STP extraction method (Sharpley, 1995; Daniel et al., 1993; Pote et al., 1999), and site (such as hydrology, management, etc.) (Sharpley et al., 1996; Pote et al., 1996). Moreover, the relationship is dependent on the time gap following litter application (Andraski and Bundy, 2003). Pote et al. (1999) showed that the effects of STP levels on DRP concentrations in runoff are not always consistent across soil series, and much of the difference can be attributed to soil infiltration characteristics (hydrology). This implies that knowledge of soil infiltration characteristics (site hydrology) can improve the usefulness of STP data for estimating DRP concentration in surface runoff.

Because the relationship between DRP and STP is dependent on many factors, management alternatives based solely on STP may lead to ambiguous conclusions, particularly when different soils are compared (Hooda et al., 2000).

Transport of Phosphorus

The first steps in the transport of DRP into surface runoff are desorption, dissolution, and extraction of phosphorus from soil, crop residues, and surface-applied commercial fertilizer and manure. These processes occur as rainfall interacts with a thin layer of surface soil (1 to 2.5 cm) before leaving the field as surface runoff (Sharpley et al., 1994). Phosphorus concentrations in subsurface flow from pasture systems were found to be at lower concentrations than the levels usually considered to cause eutrophication. On the other hand, phosphorus concentrations transported in surface runoff events, especially those occurring immediately following litter application, are well above levels that pose a threat to water quality (Owens and Shipitalo, 2006).

The main factors affecting the transport of phosphorus to surface waters are erosion and runoff. Because phosphorus is attached to soil materials, erosion largely determines the particulate phosphorus (PP) transport from cultivated fields. Phosphorus in surface runoff from pastures is generally dominated by DRP (over 90%), which is, for the most part, immediately available for biological uptake. Hence, the need to minimize the offsite transport of DRP in surface runoff from pasture systems, which otherwise may have an immediate impact on water quality. The offsite transport of DRP amount in surface runoff is a function of site hydrology, soil type, STP, type and amount of applied phosphorus, and time after application (Sharpley and Rekolainen, 1997; Storm et al., 1996b).

Materials and Methods

Greenhouse Controlled Rainfall Simulation Study

Soil Collection, Box Filling, and Grass Establishment

The soil series used for the experiments were Tonti and Nixa, which are representative pasture soils of high poultry producing areas of the Ozark highlands. Tonti series was on the crests of the hills, and Nixa series was on the sideslopes of the hills for both pasture sites (USDA-SCS, 1994). Nixa (11% sand, 72% silt, and 17% clay) and Tonti (8% sand, 78% silt, and 14% clay) were collected from the topsoil, i.e., 10 to 15 cm (4 to 6 in.), of each pasture site that has received poultry litter application. One of the sites was heavily litter-treated (20 years; high STP, 309 mg kg^{-1} per Mehlich 3 soil P extraction), and the other site was moderately litter-treated (5 years; low STP, 77 mg kg^{-1} per Mehlich III soil P extraction). The soil sample extractable phosphorus was either not correlated (e.g., water-soluble phosphorus) or weakly correlated (e.g., percent saturation of Al and Fe oxides by phosphorus, P_{sat}) as determined for all soil samples for both the greenhouse and field plot studies (Friend, 2003). The results obtained by Friend (2003) indicated that the DRP content of soils from pasture sites that received poultry litter application was controlled by factors such as time, soil chemical processes (i.e., adsorption/desorption), site hydrology, and transport processes.

Seventy-two experimental plastic boxes were constructed, each 0.5 m wide, 1 m long, and 0.15 m deep, with nineteen 6 mm drain holes drilled in the bottom. The soils were well mixed using a mechanical cement mixer prior to filling the boxes. A permeable weed-stopper fabric was placed at the bottom of the boxes to prevent loss of soil through the holes. The boxes were filled to a depth of 10 cm by adding successive amounts of soil and packing the soil to a typical field bulk density (1.5 g cm^{-3}) of the pasture sites. This resulted in 18 boxes per soil type and STP level. Sets of six boxes were placed on racks at a slope of 5%, which was a typical slope of the field plots.

In November 2001, a mixture of perennial ryegrass *Lolium perenne* L.), fescue (*Festuca arundinacea*), and bermudagrass (*Cynodon dactylon*) seed was planted to establish vegetation similar to that of pastures in the Ozark region. The grass was cut and maintained to a height of 5 cm starting from 5 January 2002 to the end of the experiment.

Surface Runoff, Irrigation, Time Interval, and Rainfall Simulator Design

Prior to the start of the experiment, rainfall was applied to the pasture boxes at a rate to maintain a good pasture growth and minimize drainage and leaching of soil phosphorus. We used the Soil and Water Assessment Tool (SWAT) hydrologic model to design a rainfall and irrigation sequence. SWAT is a physically based basin-scale model that is computationally efficient and uses readily available data inputs (Neitsch et al., 2005). It was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soil, land use, and management conditions over long periods of time (Arnold et al., 1998; Neitsch et al., 2002). The simulation was carried out for a watershed size of 75 km^2 with a single hydrological response unit under pasture land use and good management practices. The Captina-Nixa-Tonti soil series and a 50-year rainfall record (1 January 1950 to 30 April 2000) from the Kansas station in Delaware County, Oklahoma, were used as inputs (NCDC, 2002). The soil types were the common types predominantly used for pasture in the Ozark highlands of southwest Missouri and northeast Oklahoma. The average annual evapotranspiration and surface runoff simulated by SWAT were 936 mm and 220 mm, respectively.

We defined time to runoff start as the time required for a given rainfall intensity to initiate runoff. Rainfall duration was the time to runoff plus 30 min of continuous runoff, which varied from box to box depending on box hydrologic characteristics. A preliminary rainfall simulation experiment with an intensity of 75 mm h^{-1} was carried out to determine the rainfall amount required to initiate runoff from 24 greenhouse boxes. Based on this experiment, an average 54.5 mm of rainfall was applied to each pasture box, which includes 17 mm of rainfall to initiate surface runoff and 37.5 mm of rainfall to generate 30 min of continuous runoff. Eight runoff events were planned for the study to closely match the surface runoff predicted by SWAT (220 mm). Thus, for eight runoff events, at 54.5 mm per event, 436 mm of rainfall was required. The remaining 500 mm (from the total annual ET of 936 mm) was used to irrigate the greenhouse boxes. Irrigation frequency was planned once (14.3 mm) or twice (7.6 mm) a week depending on the level of ET in the greenhouse and the need to maintain good pasture growth. During this experiment, irrigation was not needed until 25 days after litter application.

DRP in surface runoff from litter applied to pastures decreases rapidly and exponentially with time following rainfall (Storm et al., 1996b). Based on the study by Storm et al. (1996b), it was hypothesized that 210 days after litter application, the DRP level in runoff from the pasture boxes will approach the background (soil phosphorus) level. Eight rainfall simulations were designed for the experiment using a statistical approach that followed an exponential decay equation (Storm et al., 1996b). The time intervals between successive rainfall simulations were determined for a time period between 1 and 210 days following the experimental design. Time intervals were rounded to the next whole day. The time intervals between the eight successive rainfall simulations, from the first to the last, were 1, 3, 3, 4, 7, 14, 30, and 148 days, which correspond to 1, 4, 7, 11, 18, 32, 62, and 210 days after litter application, respectively. These are also referred to as rainfall simulations 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Rainfall simulation 8 (210 days after litter application) was not carried out since the DRP in the runoff from rainfall simulation number 7 (day 62) was not significantly different (α = 0.05) from the background level (control DRP). Litter was applied 24 h prior to starting the first rainfall simulation at the rate of 6.7 Mg ha^{-1} to pre-saturated boxes. After this, the RRS was applied as shown in table 2.

The single-nozzle rainfall simulator assembled for this study had a TeeJet spray nozzle with a spray angle of 110° at an operating pressure of 103 kPa. It was calibrated to a 94%

uniformity coefficient over the rack of six boxes at a rainfall intensity of 75 mm h^{-1}. The nozzle had a capacity of 22.7 L min^{-1} and was centered at a height of 3 m over the rack. Both rainfall and runoff start times were recorded using stopwatches for each box throughout the study. Runoff rates were recorded manually for each box at 2 min time intervals using a calibrated 20 L runoff collection bucket.

Experimental Treatments, Design, and Statistical Analysis

The experimental treatments used for this study were composed of three factors. First, poultry litter was applied at rates of 0.0 and 6.7 Mg ha^{-1}. Poultry litter was analyzed using the inductively coupled plasma method after digestion with nitric acid. The litter had a total P content of 1.9% on dry basis (table 1). Second, the two soil series, Nixa and Tonti, which were collected from two different pasture sites, differed mainly in STP as analyzed using the Mehlich 3 extraction procedure (Mehlich, 1984). Two STP levels were used: 309 mg P kg^{-1} of soil (n = 8, standard deviation = 39 mg P kg^{-1}), and 77 mg P kg^{-1} of soil (n = 8, standard deviation = 5.8 mg P kg^{-1}). These two STP levels are referred to as high and low. Third, the rainfall/runoff sequence was applied at three levels, i.e., RRS1, RRS2, and RRS3. The RRS treatment refers to whether runoff-producing rainfall events started on the first rainfall simulation (day 1), second rainfall simulation (day 4) or third rainfall simulation (day 7) after litter application (table 2). As shown in table 2, the RRS treatment included a rainfall event without runoff for RRS2 and RRS3. Time after litter application is also inherently included, which helped to characterize the time trend effect of the above treatments on DRP loss in surface runoff.

There were 24 experimental boxes for each RRS. A non-runoff producing rainfall simulation was achieved by applying rainfall for a duration shorter than the time to initiate runoff. As a result, RRS2 and RRS3 boxes received approximately 19 and 38 mm of non-runoff producing rainfall prior to their first runoff event, respectively.

A $2 \times 2 \times 3$ factorial arrangement of treatments of poultry litter application rate, STP, and RRS, with ten replications for poultry litter treated boxes and two replications for controls, was utilized. Analysis of variance (ANOVA) procedures using PROC MIXED of SAS (SAS, 2003) were used to assess the effects of RRS, poultry litter application, STP, and time after litter application on DRP in surface runoff using an alpha level of 0.05. Time after litter application was considered as a repeated measure and modeled accordingly with a REPEATED statement and a TYPE option in PROC MIXED. A probability level of 0.05 was considered significant.

Table 1. Poultry litter chemical analysis.

Element	% on dry basis	% on "as-is" basis
Total N	3.08	1.97
Total P[a]	1.94	1.24
Total K	2.82	1.80
Total Ca	2.86	1.82

[a] Based on inductively coupled plasma analysis after nitric acid digestion at the Agricultural Diagnostic Laboratory of the University of Arkansas, Fayetteville, Arkansas.

Table 2. Experimental setup for rainfall/runoff sequence and days after litter application.

Rainfall/Runoff Sequence[a]	Time (days)[b]						
	1	4	7	11	18	32	62
RRS1	RO	RO	RO	RO	RO	RO	RO
RRS2	NR	RO	RO	RO	RO	RO	RO
RRS3	NR	NR	RO	RO	RO	RO	RO

[a] RRS1, RRS2, and RRS3 represent runoff-producing rainfall events starting from days 1, 4, and 7 after litter application, respectively.

[b] Number of days after litter application. RO = runoff-producing rainfall event, and NR = non-runoff-producing rainfall (rainfall without surface runoff). Rainfall was approximately 19 mm per simulation.

DRP Analysis

Thirty minutes of surface runoff was collected for each box, and a 60 mL composite sample was taken from each box for analysis. The samples were then filtered (0.45 μm) within 2 h of collection and stored at 4°C until analyzed. The colorimetric molybdenum-blue method of Murphy and Riley (1962) was used to determine DRP of filtered runoff samples. Because more than 90% of phosphorus loss from pastures is as DRP (Edwards and Daniel, 1993; Storm et al., 1995; Storm et al., 1996b), total phosphorus was not considered for this study.

Field Plot Rainfall Simulation Study

The field plot component of the study was initiated in July 2001 to investigate the effects of poultry litter and time after application on DRP concentrations in surface runoff from pasture fields. The study site was located 32 km (20 mi) southwest of Neosho in southwest Missouri. It was the site where the low-STP Nixa and Tonti soils were collected for the greenhouse study. The selection of this site over the high-STP pasture site (the source for the high-STP Nixa and Tonti soils for the greenhouse study) was mainly based on the expectation that lower-STP soils will show a larger change in DRP concentration following litter application. The plots were built following protocol described by the National Research Project for Simulated Rainfall - Surface Runoff Studies (SERA-17, 2001). The plots were 1.8 m wide and 2.0 m long. Metal borders, 15.0 cm tall, were installed on three sides and placed 5 cm into the ground to prevent lateral flow between the plots. A fourth border was placed lengthwise down the center of each plot, splitting it into two individual plots, each 0.9 m × 2.0 m (fig. 1). Ten of these sets were built: five for Nixa soil and five for Tonti soil. The average slope of the plots for both soils was about 5%. Along the bottom of each plot, a trough made of 10 cm diameter PVC pipe running into a 13.2 L bucket was placed into epoxy-painted cement to collect the runoff. The rainfall simulator used was the same as in the greenhouse study. The vegetation was cut to a height of 5.0 cm one week before the start of the rainfall simulation study and saturated 24 h before the actual rainfall simulation. Because the runoff from each plot was greater than the volume of the collection bucket, a peristaltic pump was used to transfer runoff from the small bucket into a larger (113 L) collection barrel. The runoff was sampled and placed on ice for transport back to Stillwater, Oklahoma, for analysis. The initial analysis of DRP was performed within 48 h of sample collection, and the remaining sample was frozen for possible future analysis similar to the greenhouse study.

Experimental Treatments, Design, and Statistical Analysis

The experimental treatments used for the field study were composed of two factors: (1) poultry litter applied at a rate of 0.0 and 6.7 Mg ha^{-1}, which is obtained from the same farm as the greenhouse study, and (2) time after litter application

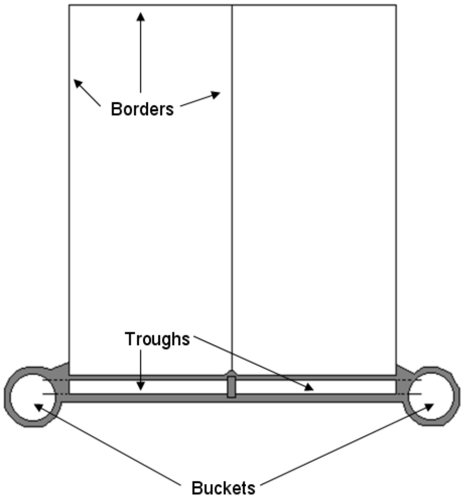

Figure 1. Sketch of field plots used for the experiment (source: Friend, 2003).

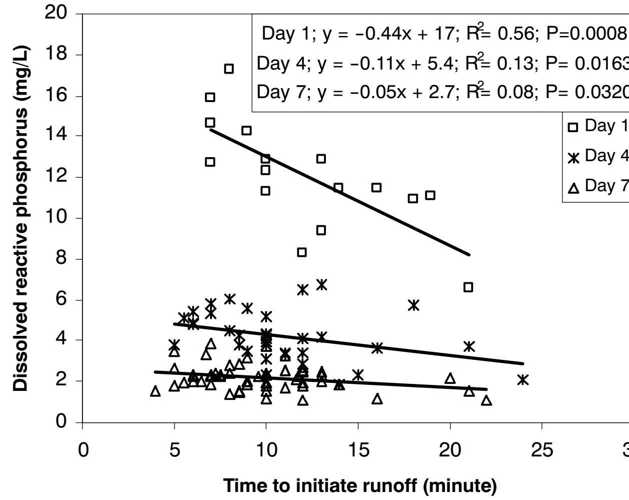

Figure 2. Significant effect of time to initiate runoff on DRP in surface runoff from litter-treated pasture boxes.

(days). There were 20 pasture field plots, i.e., ten per soil series. All plots were subjected to background rainfall simulation to determine the effect of soil phosphorus content on DRP concentration in surface runoff. Poultry litter was applied 24 h prior to the start of the actual experiment. Eight plots received litter, and two served as control for each soil series. Rainfall simulation was carried out on 1, 35, 161, and 222 days after litter application. The same ANOVA procedure as used in the greenhouse study was used to assess the effects of poultry litter application rate and days after litter application on DRP concentration in surface runoff.

Results and Discussions

Time to Runoff Start and Runoff Depth

Greenhouse and Field Plot Studies

Since rainfall intensity and runoff duration were constant in both studies, variation in time to runoff reflects differences in box infiltration (hydrology), which includes initial soil moisture levels. To minimize the effect of initial soil moisture content, the boxes or field plots were saturated with 11.4 mm of water prior to the start of the rainfall simulation experiment.

Time to runoff start and runoff depth (volume) were inversely related for the given rainfall intensity and 30 min of runoff duration. With increased time to initiate runoff, the infiltrated amount of rainfall increased, which resulted in less runoff for the fixed runoff duration. Time to initiate runoff along with the associated infiltrated rainfall had a highly significant effect ($p < 0.0001$) on runoff generated from pasture boxes despite the high variability of the data. It had also a highly significant effect on DRP concentrations in surface runoff for rainfall simulations carried out on day 1 (fig. 2). This could be due to the downward transport of DRP in infiltrated water and resulting soil P fixation or loss from the box system. The downward transport of DRP in pasture soils is desirable, as phosphorus concentrations in subsurface flow from pasture systems were found to be at lower concentrations than the levels usually considered to cause eutrophication. On the other hand, phosphorus concentrations in surface runoff events, especially those occurring immediately following litter application, are well above levels that pose an environmental surface water quality problem (Owens and Shipitalo, 2006). As time to initiate runoff increases (i.e., infiltrated rainfall increases), more DRP will be moved vertically into the soil, provided that the source for DRP is not limited. Time to initiate runoff was also statistically significant on days 4 and 7 after litter application, but the correlation was not strong. With successive non-runoff/runoff producing rainfall events and a single litter application rate, less DRP will be available for vertical transport by the infiltrated rainfall. As a result, the effect of time to initiate runoff or infiltrated rainfall amount becomes less significant on DRP concentrations in runoff with increasing days after litter application. The effect of time to initiate runoff became nonsignificant for the whole experimental data set.

The results obtained from both the box and field plot studies suggest the importance of minimizing surface runoff from the first one or two runoff events following surface application of poultry litter to pasture fields. Field plots or boxes with high infiltration volume (e.g., longer time to initiate runoff, large amount of infiltrated rainfall and/or low runoff volume) had lower DRP concentrations, indicating the importance of infiltration characteristics in DRP transport. An increase in the infiltrated rainfall amount minimizes the offsite transport of phosphorus to water resources, as long as the downward leaching and subsurface transport of phosphorus to nearby sensitive water resources is controlled.

Trend of Average DRP in Surface Runoff

Greenhouse Rainfall Simulation Study

The DRP concentration in surface runoff from litter-treated boxes was higher compared to that from controls. Because the experimental soils differ only in STP, and STP had no significant effect on DRP content in runoff following litter application, the DRP amount in runoff was averaged separately for all litter-treated boxes and controls. The averaged DRP concentration decreased exponentially with increasing time after litter application (fig. 3). The averaged DRP concentration from litter-treated boxes approached asymptotically to the DRP from the control boxes. Although they were not significantly different, averaged litter DRP (0.46 mg L^{-1}) was higher than control DRP (0.25 mg L^{-1}) on day 62 (table 3 and fig. 3). An exception to this general trend occurred on day

Table 3. Statistical summary of the effects of poultry litter, STP, and rainfall/runoff sequence on box averaged DRP.[a]

Rainfall/ Runoff Sequence[b]	Poultry Litter Total P Rate (kg ha^{-1})[c]	STP (mg kg^{-1})[d]	Time (days after litter application)						
			1	4	7	11	18	32	62
RRS1	130	309	11.70 aA	3.83 aB	2.18 aC	2.19 aC	1.05 aD	0.61 aD	0.43 aD
		77	12.40 aA	3.63 aB	1.86 aC	2.03 aC	1.25 aCD	0.78 aD	0.48 aD
	0	309	0.80 bA	0.51 bA	0.46 bA	0.82 aA	0.43 aA	0.40 aA	0.24 aA
		77	1.05 bA	0.67 bA	0.45 bA	0.93 aA	0.47 aA	0.40 aA	0.33 aA
RRS2	130	309	--	4.60 aA	2.32 aB	2.21 abB	0.99 aC	0.75 aC	0.50 aC
		77	--	4.90 aA	2.27 aB	2.54 aB	1.11 aC	0.73 aC	0.46 aC
	0	309	--	0.70 bA	0.54 bA	1.06 bA	0.65 aA	0.47 aA	0.21 aA
		77	--	0.60 bA	0.51 bA	1.23 abA	0.59 aA	0.38 aA	0.28 aA
RRS3	130	309	--	--	2.30 aA	2.68 aA	1.23 aB	0.93 aB	0.48 aB
		77	--	--	2.20 aA	2.85 aA	1.22 aB	0.86 aB	0.45 aB
	0	309	--	--	0.50 bA	1.27 bA	0.56 aA	0.50 aA	0.20 aA
		77	--	--	0.50 bA	0.99 bA	0.44 aA	0.42 aA	0.21 aA

[a] Values are mean DRP (mg L^{-1}). Values followed by the same letter are not significantly different at the 0.05 probability level by the least significant difference (LSD) test. Lowercase letters indicate comparison within columns, and capital letters indicate comparison within rows.

[b] RRS1 = runoff-producing rainfall event (RPE) starting from day 1 after litter application, RRS2 = RPE starting from day 4, and RRS3 = RPE starting from day 7.

[c] Poultry litter application rate was 6.7 Mg ha^{-1} for litter received and 0.0 Mg ha^{-1} for control boxes.

[d] STP was based Mehlich 3 soil P extraction. Values are averages of eight samples for each level; standard deviations for 309 and 77 mg kg^{-1} STP levels were 39 and 5.8 mg kg^{-1}, respectively.

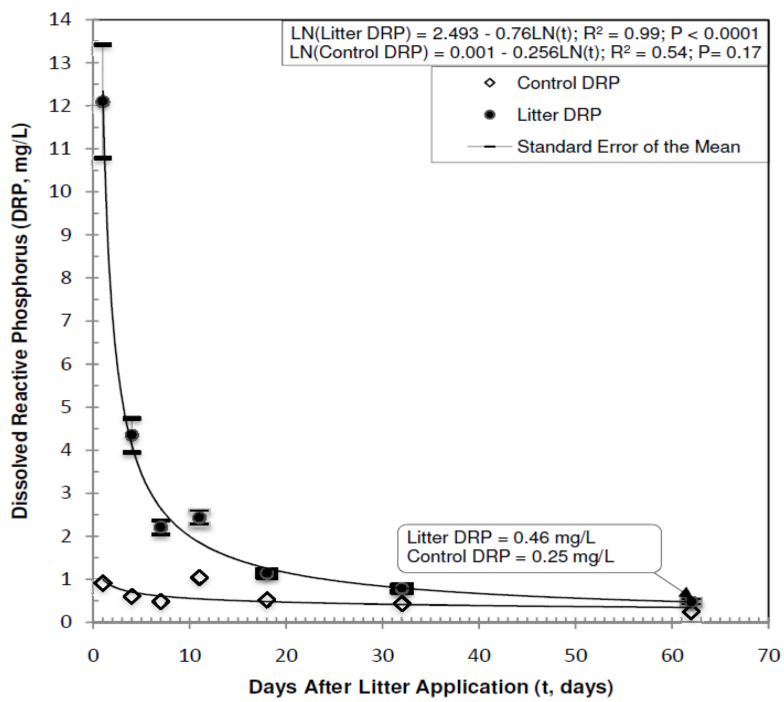

Figure 3. Trend of averaged DRP in surface runoff from control and litter treated pasture boxes in a controlled greenhouse experiment using a simulated rainfall.

11, when most boxes (including controls) showed a slight increase in DRP concentration in runoff from their respective DRP values on day 7 (table 3, figs. 3 and 4). Such phenomena were observed for the field plot study (fig. 5) and by McIsaac et al. (1995). This could be due to phosphorus transformations associated with the pasture establishment, microbial activity, extraction of more soluble phosphorus from grass residue (pasture clippings) left in the boxes, or soil chemical processes (i.e., adsorption/desorption).

Field Plot Rainfall Simulation Study

Similar to the greenhouse experiment, DRP from field plot pastures spiked immediately following litter application (fig. 5). It then decreased rapidly, the greatest decrease being between the first and second rainfall simulation (6.6 to 0.64 mg L^{-1}; 90%). The averaged DRP in the first runoff event from the field plots was less than that from the greenhouse boxes (12.1 mg L^{-1}), probably due to the large size of the field plots and the associated larger runoff volume and dilution. In addition, the field plots received 78 mm of natural rainfall between the two rainfall simulation events (NOAA,

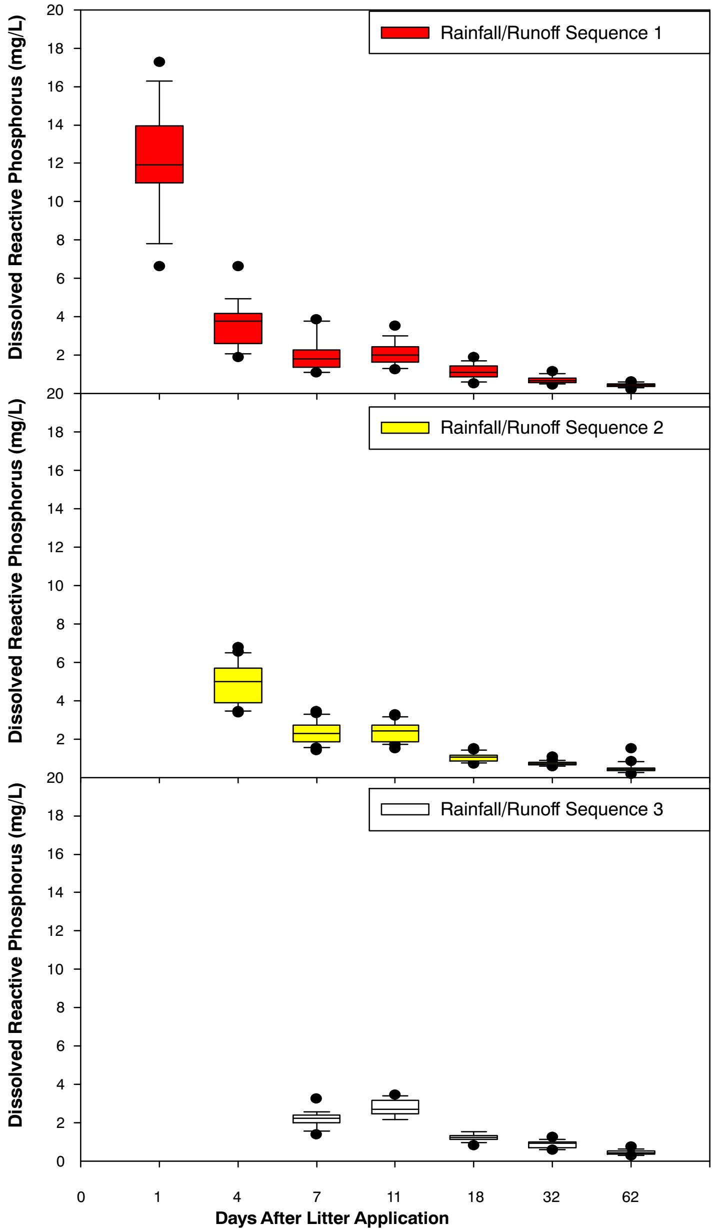

Figure 4. Declining effect of rainfall/runoff sequences on DRP with increase in days after litter application from litter treated pasture boxes.

2003). This rainfall probably played a role in the additional transport and/or transformation of litter DRP from the field plots. This was expected, as the field plot study was not a controlled experiment. Overall, the pasture field plot experiment corroborates the greenhouse study in which the averaged DRP, after an initial spike in the first surface runoff event, decreased rapidly between the two successive rainfall simulations on days 1 and 35 after litter application. It also corroborates the greenhouse study in which a rainfall event combined with time interval reduced DRP concentrations. DRP increased slightly for runoff events on days 161 and 222 after litter application (1.1 and 1.3 mg L^{-1}, respectively), possibly due to increased moisture and microbial activity associated with the spring season or soil adsorption/desorption processes. This phenomenon was also observed in the greenhouse. After the second rainfall, there was no statistical difference between the treated plots and the control plots (table 4).

Greenhouse and Field Plot Rainfall Simulation Studies

After the start of the rainfall simulation experiment for both the greenhouse and field plot studies, Friend (2003) analyzed soil core samples (top 2 cm) taken from the boxes and field plots before each successive rainfall simulation. Results indicated that the saturation of the soil with phosphorus (P_{sat}) was highly correlated ($p < 0.01$) to pore water, STP, and water-soluble phosphorus, suggesting that adsorption/desorption processes control soil solution phosphorus. From the analysis, Friend (2003) concluded that the DRP content of soils from pasture sites that received poultry litter application was controlled by several factors, such as time, soil chemical processes (i.e., adsorption/desorption), site hydrology, and runoff transport processes.

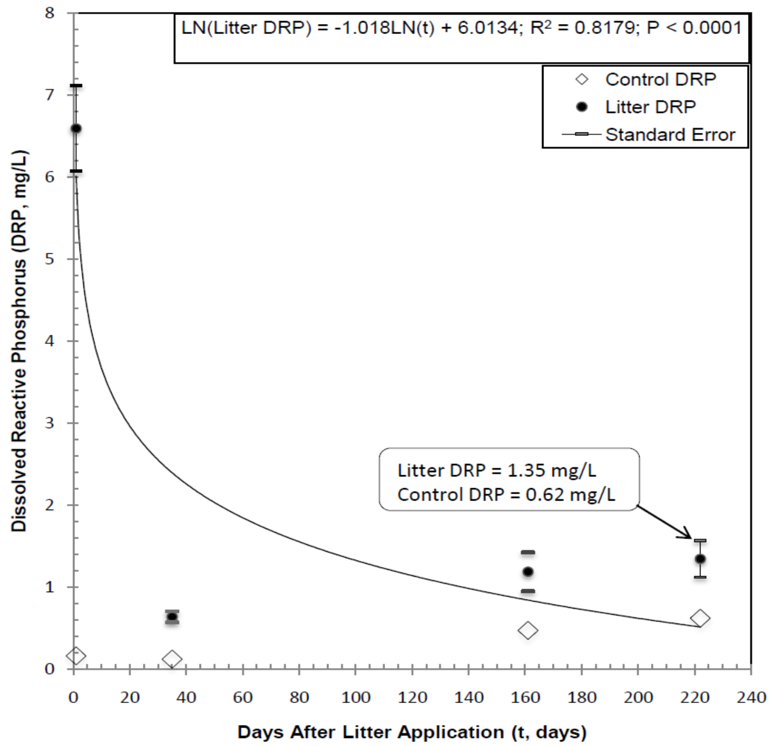

Figure 5. Trend of averaged DRP in surface runoff from control and litter treated field pasture plots using a simulated rainfall.

Table 4. Effect of litter application on the extractable phosphorus fractions of soil samples for the field plot study (source: Friend, 2003).[a]

Soil Series	Litter Application	Pore Water ($mg\ L^{-1}$)	Mehlich 3 ($mg\ kg^{-1}$)	Water ($mg\ kg^{-1}$)	P_{sat} (%)
Tonti	No	1.94 a	51.3 a	14.1 a	22.8 a
Nixa	No	1.86 a	71.2 b	16.4 a	22.8 a
Tonti	Yes	6.44 b	95.0 c	25.1 b	30.0 b
Nixa	Yes	7.86 b	117 d	29.8 b	34.6 b

[a] Values within column followed by same letter are not significantly different at $p < 0.05$.

Table 5. Statistical summary of the effect of STP on DRP ($mg\ L^{-1}$) prior to litter application from pasture boxes.[a]

STP ($mg\ kg^{-1}$)[b]	Time[c] 1	2	3
309	0.57 aA	0.90 aB	0.88 aB
77	0.33 bA	0.66 bB	0.90 aC

[a] Values followed by the same letter are not significantly different at the 0.05 probability level. Lowercase and capital letters indicate comparisons within columns and rows, respectively.
[b] High (309 $mg\ kg^{-1}$) and low (77 $mg\ kg^{-1}$) using Mehlich 3 soil P extraction. Soil test was carried out prior to pasture establishment, and there was considerable time until the first rainfall simulation. However, both STP levels were subjected to identical situations even if soil P underwent transformation.
[c] Time refers to the three-time repeated rainfall simulations prior to poultry litter application.

Effect of STP on DRP

Greenhouse Rainfall Simulation Study

STP had a highly significant ($p = 0.0002$) effect on DRP in runoff from the greenhouse boxes prior to litter application (table 5). There was a slight increase in DRP from time 1 to 3 (table 5). Immediately following litter application, STP had no significant effect on DRP concentrations despite the con-

Table 6. Effect of rainfall/runoff sequence on average first runoff event DRP ($mg\ L^{-1}$) from pasture boxes.[a]

Treatment	STP[b]	Rainfall/Runoff Sequence[c] RRS1	RRS2	RRS3
Litter treated	309	12.40 aA	4.90 aB	2.20 aC
	77	11.70 aA	4.60 aB	2.30 aC
Average		12.05	4.75	2.25
Control	309	1.10 bA	0.60 bA	0.50 bA
	77	0.80 bA	0.70 bA	0.50 bA
Average		0.95	0.65	0.50

[a] Values followed by the same letter are not significantly different at the 0.05 probability level by the least significant difference (LSD) test. Lowercase and capital letters indicate comparisons within columns and rows, respectively.
[b] Low (77 $mg\ kg^{-1}$) and high (309 $mg\ kg^{-1}$) Mehlich 3 soil P extraction.
[c] RRS1 = first runoff-producing rainfall event (RPE) starting from day 1 after litter application, RRS2 = RPE starting from day 4, and RRS3 = RPE starting from day 7.

siderable difference of the two soils in STP (tables 3 and 6; fig. 3). The highly soluble phosphorus in the litter likely served as the primary source of DRP in surface runoff. In other words, surface poultry litter application masked the STP vs. DRP relationship.

Field Plot Rainfall Simulation Study

Soil test phosphorus had a non-significant effect on DRP from the field plot studies before litter application. This differed from the greenhouse boxes, where STP had a significant effect on DRP in runoff. It also remained non-significant following litter application.

Effect of Rainfall/Runoff Sequence

Greenhouse Rainfall Simulation Study

A rainfall/runoff sequence treatment was added to the experiment to study the effect of time between litter application and the first surface runoff event on DRP concentrations in runoff in combination with or without a non-runoff producing rainfall event from boxes that received poultry litter application. All boxes received rainfall starting from day 1. However, only RRS1 boxes were subjected to surface runoff producing rainfall events on day 1 (table 2).

The effect of RRS on the first runoff event DRP concentration is summarized in table 6. Boxes that received the RRS1 treatment had the highest average DRP concentration (12.1 mg L^{-1}) in surface runoff event on day 1 after litter application (table 6 and fig. 4). For RRS1, DRP concentration ranged from 6.6 to 17.3 mg L^{-1} depending on box infiltration and soil characteristics (fig. 4). Considering the offsite transport of phosphorus from pasture systems, this could be considered the worst-case scenario. Immediately after litter application, poultry litter is vulnerable to significant interaction with surface runoff water. The average DRP concentration in runoff from RRS2-treated pasture boxes at the first runoff event (day 4) was 4.75 mg L^{-1}, and it ranged from 3.37 to 6.77 mg L^{-1} (fig. 4). Compared to RRS1-treated boxes, the average decrease in DRP concentration in runoff from RRS2-treated boxes was about 60% (7.26 mg L^{-1}). Similarly, for RRS3-treated boxes, the average concentration of DRP in surface runoff collected at the first runoff event (day 7) was 2.25 mg L^{-1}, and it ranged from 1.39 to 3.27 mg L^{-1} (fig. 4). Compared to RRS2-treated boxes, the average decrease in DRP for the RRS3-treated boxes was about 53% (2.50 mg L^{-1}). This would change to 81% (9.76 mg L^{-1}) when the comparison is made with RRS1-treated boxes. For all RRS treatments, the time trend of the DRP indicates less variability and an exponential decrease with increasing time (days) after litter application, as shown in figure 4.

The significant effect of rainfall/runoff sequence on DRP concentration emphasizes that a rainfall event without runoff combined with a longer time interval between litter application and the first runoff event reduces the initial DRP concentration in runoff from litter-treated pastures. The smallest initial DRP was observed for RRS3-treated boxes, which were subjected to two non-runoff producing rainfall events and a longer time interval between litter application and first runoff event (7 days). This may be due to the onset of phosphorus cycling, which changes more soluble phosphorus in litter to less soluble forms, or transport of soluble phosphorus into the soil by infiltrated rainfall. Rainfall/runoff sequence had no significant effect on DRP from control pasture boxes (table 6).

As shown in table 6, the effect of different RRS treatments became significant as the time interval increased. More DRP concentrations will be expected in runoff from pastures if litter application is made during periods of the year when runoff-producing storms are likely or when there is only a short time interval between litter application and occurrences of runoff events. The importance of the time interval until the first runoff has been pointed out by various researchers (Pierson et al., 2001; Nash et al., 2000; Sharpley, 1997; Storm et al., 1996b; Edwards and Daniel, 1993) and corroborated by this study along with the importance of the non-runoff producing rainfall event. DRP concentration in surface runoff was extremely sensitive to a non-runoff producing rainfall event and to the time interval between litter application and first surface runoff event. Although they did not include RRS treatment, Westerman and Overcash (1980) observed a 90% reduction in phosphorus amount in runoff as the time interval increased from an hour to three days after litter application. This clearly emphasizes the importance of the timing of phosphorus application relative to the likelihood of runoff-generating intense storm or runoff events.

Effect of Poultry Litter Application

Greenhouse Rainfall Simulation Study

Surface application of poultry litter to boxes increased the DRP in surface runoff. The increase in DRP was greatest for RRS1 and least for RRS3 treated boxes. Due to the highly significant litter vs. time interaction ($p < 0.0001$), an analysis of the simple effects of litter versus time was made before drawing any inference. Pearson correlation analysis indicated that DRP in runoff from pasture boxes was highly dependent on time (days) after litter application ($r = -0.65$, $p < 0.0001$). Table 3 shows a statistical summary of the effects of poultry litter, STP, and RRS on DRP. Poultry litter had a highly significant effect on DRP in surface runoff from treated boxes compared to that from control boxes until 18 days after litter application. Its effect became non-significant (at the 5% significance level) after day 18 for any level of STP or RRS.

Field Plot Rainfall Simulation Study

Poultry litter had also a highly significant effect on DRP in runoff from field plots until 35 days after litter application. DRP decreased rapidly after an initial spike following litter application, thereby corroborating the greenhouse experiment. However, for the same poultry litter application and rainfall simulation rate, the field plots experienced a lower initial spike and rapid decline in average DRP. The natural rainfall of 78 mm received between day 1 and day 35 after litter application, the larger plot size, and the associated runoff volume and dilution might have contributed to this.

Effect of Time After Litter Application

Greenhouse and Field Plot Studies

Time (days after litter application) had a highly significant effect on DRP in surface runoff collected from the boxes ($p < 0.0001$). With increasing time, DRP is likely to move into the soil with infiltrating water or transform into less soluble forms. Due to these reasons, the effect of applied litter decreased with time. DRP decreased the most at the beginning, and then it gradually approached asymptotically the DRP concentration in runoff from boxes and field plots that did not receive litter (controls). The decline in DRP (litter vs. control) with increasing time after litter application was statistically significant until day 18 (greenhouse) and day 35 (field plots). Some time between 18 and 32 days (greenhouse) and between 35 and 161 days (field plots) after litter application, the effect of poultry litter was non-significant compared with the controls (figs. 3 and 5). Similar to the litter-treated boxes, DRP decreased rapidly with time (days) for the greenhouse control boxes (fig. 3); however, this was not observed in the field plot study (fig. 5).

Summary

The objectives of this study were to investigate the effects of STP, surface application of poultry litter (source), rainfall/runoff sequence, and time after litter application (management) on DRP in surface runoff from boxes in a greenhouse controlled study. The second objective was the investigation of the effect of poultry litter and time after application on DRP in surface runoff from pasture field plots. The field plot study was also carried out to assess if the findings corroborate the greenhouse study. A simulated rainfall was utilized for both studies. Rainfall intensity and runoff duration were held constant throughout the experiment. Time to initiate runoff varied from box to box and from plot to plot depending on soil hydrology and infiltration characteristics. Runoff produced from each box or plot was manually recorded at 2 min intervals, and a sample was taken at the end of 30 min of runoff and analyzed for DRP. Phosphorus transport in runoff from pastures is dominated by DRP, which may result in eutrophication of receiving water bodies.

Greenhouse Rainfall Simulation Study

For the greenhouse study, poultry litter, rainfall runoff sequence (RRS), and time after litter application had a highly significant effect on DRP concentrations in runoff from pastures. The significant STP effect on DRP concentration in runoff prior to litter application was masked following litter application. This indicates that litter phosphorus served as the primary source of DRP concentrations in the surface runoff collected from the boxes.

The effect of poultry litter application on DRP in runoff was also dependent on the time interval between litter application and the first runoff event, and whether there was a non-runoff producing rainfall event during this interval (RRS). The highest averaged DRP amount was observed in runoff collected from boxes with the shortest time interval (1 day) between litter application and first surface runoff event (RRS1). A rainfall event without runoff significantly reduced the effect of poultry litter application on DRP concentration in the first surface runoff event. A longer time interval (RRS3; 7 days) combined with two non-runoff producing rainfall events resulted in the highest reduction (as much as 83%) in DRP concentration in runoff compared with RRS1. Litter-treated boxes that were subjected to non-runoff producing rainfall exhibited a reduction of more than 50% in DRP in the first runoff event during the successive rainfall simulations (i.e., RRS1 and RRS2, and RRS 2 and RRS3). The time trend effects of RRS on DRP indicated less variability and an asymptotical approach to the control DRP from above.

Time to initiate runoff (i.e., difference of rainfall and runoff duration) had a significant effect on DRP concentrations in surface runoff from the boxes on day 1 after litter application. Although its effect was statistically significant on days 4 and 7 after litter application, the correlation was not strong. Any practice that minimizes runoff or increases soil infiltration would minimize offsite transport of DRP concentration, especially from pastures with the shortest time interval between litter application and first runoff event.

An exponential decrease defined the relationship between DRP and time after poultry litter application, indicating that poultry litter becomes less available over time for a single application rate (6.7 Mg ha^{-1}). Poultry litter application had a significant effect on DRP concentration in surface runoff until 18 days compared to controls. Some time between day 18 and 32 after litter application, the effect of litter was not significant compared with controls, although observed litter DRP (0.46 mg L^{-1}) was higher than control DRP (0.25 mg L^{-1}) at the end of the experiment (day 62). Time had a highly significant effect on DRP concentration in surface runoff from litter-treated boxes in two ways: time interval between litter application and first runoff event (that ranged from 1 to 7 days) in combination with a rainfall event without runoff, and time after litter application (ranging from 1 to 62 days).

Field Plot Rainfall Simulation Study

For field plots, poultry litter and time after litter application had a significant effect on DRP in surface runoff. Soil test phosphorus had no significant effect either before or after litter application.

Poultry litter had a highly significant effect on DRP concentration in surface runoff from the pasture field plots. Infiltrated rainfall had a highly significant effect on DRP on the first runoff event ($p < 0.001$) but became insignificant thereafter. The field experiment corroborated the greenhouse study, in which an exponential decrease of DRP was exhibited with time. The effect of poultry litter application on DRP became statistically non-significant sometime between 35 and 161 days after litter application.

The decline in the magnitude of DRP in runoff between rainfall simulations 1 and 2 was greater (90%) for the field plots than for the greenhouse boxes (64%). The field plots also received 78 mm of natural rainfall between the two rainfall simulation events. This rainfall probably played a role in the transport and/or transformations of litter DRP from the plots due to the observed rapid decrease in DRP. This was expected, as the field plot study was not a controlled experiment and was subject to natural rainfall, unlike the greenhouse study. The averaged DRP in the first runoff event from the field plots was less than that from the greenhouse boxes, probably due to the large size of field plots, larger runoff volume, and associated dilution. Overall, the pasture field plot experiment corroborates the effect of time to initiate runoff and infiltrated rainfall on DRP concentrations in the first surface runoff event, and the rapid decline of DRP in runoff with time.

Conclusions and Recommendations

When runoff-producing rainfall events occurred immediately following poultry litter application to saturated pastures, significantly greater DRP concentrations were measured for the first runoff events in both the greenhouse and field plot studies. Hence, surface application of poultry litter should be minimized during early spring (wet soil condition), when runoff events that can transport litter phosphorus to nearby water resources are likely. The DRP levels from first runoff events were above levels that pose a threat to surface water quality.

After one or two non-runoff producing rainfall events, DRP concentrations in the first runoff events were reduced significantly ($p < 0.05$), indicating the effect of a rainfall event without runoff (rainfall/runoff sequence) in combination with time to first runoff from pastures (greenhouse study). The reduction in DRP ranged from 50% to 83% for the pasture boxes. This indicated that irrigation of pastures with a non-runoff producing water sources following litter application can minimize DRP transport in runoff. This is due to transformations and vertical transport of DRP into the soil, thereby suggesting that incorporation of litter DRP into the soil minimizes offsite transport of DRP in runoff. Rainfall/runoff sequence had no significant effect on DRP concentrations from the control pastures. Pastures in the field plot study received 78 mm of natural rainfall between day 1 and day 35 after litter application. This further reduced DRP concentration in runoff rapidly and significantly from 6.6 to 0.64 mg L^{-1}. This emphasizes the importance of best management practices that increase soil infiltration and time after litter application, which in combination appear to reduce DRP concentrations in runoff. This study showed that DRP in runoff can be reduced, and thereby the offsite impacts on surface water quality can be minimized. It is recommended that additional research be conducted to investigate the effect of no rainfall treatment after litter application (keeping the pasture alive) and to determine the controlling factor, i.e., rainfall without runoff, a time gap between litter application and first runoff event, or a combination of both. This study clearly showed the latter case.

Poultry litter and time after application rate have a significant effect on DRP concentrations in runoff from pastures. In this study, much of the DRP (as much as 55% of the total DRP in seven runoff events in the greenhouse study) is lost during the first runoff event following the single poultry litter application, i.e., the worst-case scenario for surface water quality. Similar to the greenhouse study, the effect of poultry litter on DRP concentrations in runoff decreased rapidly from its initial spike with increasing days after litter application in the field plot study. The rate of decline in DRP in runoff was higher for the field plots, probably due to 78 mm of rainfall received, the larger plot size, and the associated runoff volume and dilution.

An increase in the amount of infiltrated rainfall, as indicated by increased time to initiate runoff, significantly reduced DRP in runoff from the first runoff events (greenhouse study). The correlation was stronger for day 1 than it was for days 4 and 7. The infiltration of water transported phosphorus vertically in the soil profile, reducing its viability for transport in runoff during the successive rainfall simulations. Consequently, efforts to minimize impacts on surface water quality should focus primarily on best management practices that reduce surface runoff and/or increase onsite infiltration immediately following poultry litter application.

For both the greenhouse and field plot studies, litter DRP approached the control DRP (background level) in runoff. Although not statistically significant, litter DRP was higher than control DRP in runoff from both studies at the end of the experiment, indicating the residual effect of the single litter application. While this study investigated the effect of a single application of poultry litter to pastures, efforts should be made to investigate the effect of long-term water quality impacts from repeated poultry litter applications. This has the inherent potential to elevate soil phosphorus content and DRP level in runoff, thereby promoting eutrophication and subsequent detrimental impacts to nearby water resources.

Immediately following litter application, litter phosphorus served as the primary source of DRP concentrations in the surface runoff collected from the greenhouse boxes. The significant effect of STP on DRP loss in runoff was masked following litter application. Unlike the greenhouse study, STP had no significant effect on DRP in runoff either before or after litter application in the field plot study. This was expected, as the field plot study was carried out at the low-STP pasture site.

The results obtained from the field plot study corroborated the greenhouse (controlled) study, suggesting that greenhouse studies could be used in place of field studies with the added benefit of a controlled environment to avoid unwanted or unplanned rainfall, e.g., the 78 mm rainfall that took place during the field plot study. The major factors that influence DRP from pastures receiving annual applications of poultry litter are time interval between application and first runoff event, a non-runoff producing rainfall event, and time after application.

Acknowledgements

The authors would like to thank the U.S. Environmental Protection Agency Region VI for funding the project, and Lynn Jenkins and Dan Philbrick from the USDA Natural Resources Conservation Service in Neosho, Missouri, for their assistance to undertake this study.

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NOMENCLATURE

DRP = dissolved reactive or soluble phosphorus in runoff (mg L^{-1})

P_{sat} = percent saturation of Al and Fe oxides by phosphorus

r = Pearson correlation coefficient

RRS = runoff/non-runoff producing rainfall event, i.e., rainfall/runoff sequence (RRS 1, RRS 2, and RRS 3 refer to runoff collection starting from day 1, day 4, and day 7, respectively, after litter application)

RPE = runoff-producing rainfall event

STP = soil test phosphorus